

# Impulsive enhancements of oxygen ions during substorms

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**Abstract.** It has been observed that  $H^+$  is the dominant ion species in the plasma sheet and the ring current during quiet times. However, the  $O^+/H^+$  density ratio increases with increasing geomagnetic storm and substorm activity. Energetic neutral atom (ENA) images from IMAGE/HENA reveal the rapid increase of  $O^+$  ring current at substorm expansion. Finding the cause of this substorm associated  $O^+$  enhancement is the main focus of this paper. Two possible sources are suggested: direct injection from the ionosphere and energization of the pre-existing oxygen ions in the magnetosphere. We perform numerical simulations to examine these two mechanisms. Millions of  $O^+$  are released from the auroral region during a simulated substorm by the Lyon-Fedder-Mobarry MHD model. The subsequent trajectories of these outflowing ions are calculated by solving the full equation of particle motion. A few minutes into the substorm expansion phase, an enhancement in  $O^+$  pressure is found on the nightside at  $\sim 12 R_E$ . After careful analysis, we conclude that this pressure peak is coming from energization of the pre-existing  $O^+$  in the plasma sheet. The direct injection mechanism will introduce a significant time lag between strong ionospheric outflow and magnetospheric enhancement so that it cannot explain the observed  $O^+$  bursts. Using the temperature and density established by the test-particle calculations as boundary conditions to a ring current model, we calculate the  $O^+$  fluxes and the corresponding ENA emissions during the model substorm. We are able reproduce observable features of oxygen ENA enhancements as seen by IMAGE/HENA.

## 1. Introduction

Oxygen ion is one of the major ion species in the plasma sheet and ring current regions that bears many important and unique features. Unlike magnetospheric  $H^+$ , which originate from both the solar wind and the ionosphere,  $O^+$  exclusively originate from the ionosphere [Moore and Delcourt, 1995; Moore et al. 2001; Moore and Horwitz, 2006]. Oxygen ions thus act as tracers of ionospheric influences on the magnetosphere. The upward flow of ionospheric  $O^+$  is primarily from the auroral zone and is powered by solar wind energy dissipated into the ionosphere [Moore et al., 1999]. The outflow and heating of  $O^+$  alters the density, pressure and ion composition in the magnetosphere. Since the lifetimes are different for different ion species, the composition changes in the magnetosphere control the recovery time scale of a magnetic storm. Hamilton et al. [1988] suggested the short charge exchange lifetimes of 75–100 keV  $O^+$  are responsible for the rapid initial recovery of the major storm on 8–9 February 1986. These  $O^+$  ions can also cause the reduction of reconnection rate by decreasing of the Alfvén speed or reduction of the convection strength by momentum conservation [Winglee et al., 2002]. Owing to the relatively large gyroradius and small cyclotron frequency,  $O^+$  ions behave non-adiabatically in much of the magnetosphere, especially near the central plasma sheet and during magnetic reconfiguration. Enhanced density of these heavy ions in the plasma sheet may lead to tearing mode instabilities and triggering substorm onset [Baker et al., 1982; 1985] since the growth rate of tearing mode instability increases when the ratio of the ion gyroradius to the characteristic plasma sheet thickness rises.

The energy density ratio of  $O^+/H^+$  in the magnetosphere is small during quiet times, however, this ratio increases with increasing geomagnetic activity [Young et al., 1982; Hamilton et al., 1998; Roeder et al., 1995; Daglis 1997]. In large magnetic storms,  $O^+$  becomes the

dominant ion species. During extreme events, like the Halloween storm in October 2003, the  $O^+/H^+$  energy density ratio is as high as 10-20 [Nose *et al.*, 2005]. It is apparent that, compared to  $H^+$ , the source and energization of  $O^+$  are more responsive to storm activity, which is driven by disturbed solar wind conditions.

The  $O^+$  abundance in the magnetosphere is also sensitive to substorm activity. Using data from AMPTE/IRM, Mobius *et al.* [1987] found, after a substorm onset, flux increase in energetic (10–230 keV/e) ions in the plasma sheet and hardening of the energy spectra that are most pronounced for  $O^+$ . Daglis and Axford [1996] also found rapid enhancement of  $O^+$  fluxes in the inner magnetotail after substorm onset. From the images taken by the Imager for Magnetopause-to-Aurora Global Exploration/High Energy Neutral Atom (IMAGE/HENA) imager, Mitchell *et al.* [2003] found intense oxygen (52–180 keV) energetic neutral atom (ENA) bursts at each substorm onset. In contrast, there were weak responses in hydrogen ENA at similar energies. They suggested that the non-adiabatic acceleration of  $O^+$  during dipolarization is responsible for the observed oxygen bursts seen by IMAGE/HENA. This mechanism was previously proposed and modeled by Delcourt [2002]. Another possible source of the substorm oxygen bursts is direct injection of energetic  $O^+$  from the ionosphere [Sheldon *et al.*, 1998].

A simulation study was performed by Moore *et al.* [2005], of the formation of ring current from both solar and ionospheric plasmas. They used test particle motions in magnetospheric fields from the magnetohydrodynamic (MHD) simulation of Lyon, Fedder, and Mobarry [Fedder *et al.*, 1995; Mobarry *et al.*, 1996; Slinker *et al.*, 2001]. They chose a state reflecting steady substorm growth conditions. Particles are initiated in regions representative of the solar wind proton source upstream of the bow shock, the polar wind proton source, and the auroral zone enhanced outflows of  $O^+$ , which is named "auroral wind". Moore *et al.* [2005] found

that solar wind protons enter the ring current principally via the dawn flank, bypassing the energization processes in the midnight plasma sheet, while polar wind protons and auroral wind  $O^+$  enter the ring current through the lobes and midnight plasma sheet. Since solar wind and ionospheric ions take different paths to the magnetosphere, they are expected to respond differently to substorm dynamics in the magnetotail and experience different energization along their trajectories. In this paper, we extend the work of *Moore et al.* [2005] in two ways. First, instead of steady magnetospheric conditions, protons and  $O^+$  are released from their source regions during an MHD substorm cycle. Second, we extend the simulation into the inner magnetosphere using the Comprehensive Ring Current Model (CRCM) [*Fok et al.* 2001]. The outflowing  $O^+$  flux and energy are parameterized by instantaneous MHD density, Joule heating and field aligned potential drop [*Strangeway et al.*, 2005]. The main focuses of this paper are to test the two candidate mechanisms (non-adiabatic energization versus direct injection) responsible for  $O^+$  enhancements and to understand why protons and  $O^+$  behave differently in substorms. As *Moore et al.* [2005], ion trajectories are calculated by the test-particle code of *Delcourt et al.* [1993; 1994] in the Lyon-Fedder-Mobarry (LFM) electric and magnetic fields. With each ion assigning a source flux, the density and pressure contributed by these ions in the magnetosphere are established. With these temperature and density as boundary conditions to the CRCM, we calculate the  $O^+$  fluxes in the inner magnetosphere and the corresponding ENA emissions during the model substorm. Our simulated oxygen ENA images are compared with those from IMAGE/HENA. In the following sections, we will present some HENA observations of oxygen ENA, the details of our calculation, simulation results, and how we identify the source mechanisms for the impulsive increase of oxygen ions during substorms.

## 2. HENA Observations

HENA obtains hydrogen and oxygen ENA images in the 10-198 keV and 52-264 keV ranges, respectively. Particles enter the fan shaped outer collimators that are electrostatically charged so that any charged particles below a specified energy are swept away into the collimators and are prevented from entering the system. The remaining ENAs and photons enter a thin slit covered with a front foil. The front foil decreases the photon intensity and the penetrating ENAs create a shower of electrons that are detected by a start micro channel plate (MCP) along the slit. This electron shower acts as the start pulse, triggering a time of flight (TOF) system. The ENAs continue with a scattering angle, which depends on particle velocity, and hits the stop MCP. There, the time of the stop pulse is similarly recorded by the MCP and its two-dimensional (2D) location is determined by position-sensitive anodes. The position of an ENA in the front-foil and the 2D position on the stop MCP can now be used to compute the direction of the incoming ENA. In this way the angular resolution only depends on what angular bin size is chosen in the on board software. The angular resolution is  $6^\circ \times 6^\circ$  for hydrogen with energy less than 60 keV and for oxygen. The resolution for hydrogen greater than 60 keV is  $3^\circ \times 3^\circ$ . The scattering in the front foil is velocity dependent and determines the point-spread function (PSF) of HENA. For a hydrogen the point-spread full width at half maximum is about  $15^\circ$  for 30 keV hydrogen and about  $5^\circ$  for 100 keV hydrogen. Due to velocity dependence, the spread is larger for oxygen:  $\sim 25^\circ$  for 100 keV oxygen and  $\sim 10^\circ$  for 200 keV oxygen. A more detail description of the HENA instrument can be found in *Mitchell et al.* [2000].

The oxygen ENA signal during substorms is one of the most outstanding features in the HENA data set [*Mitchell et al.*, 2003]. At each storm-time substorm onset a significant increase of the oxygen ENA intensities can be seen coming from the nightside and low altitudes. The

increase lasts for about 20-30 minutes and then decays away on similar timescales. While the overall hydrogen intensity is higher than the oxygen intensity, the relative intensity variation of the hydrogen ENA signal is much more gradual. Figure 1 summarizes the HENA observations of the substorm injection of 28 October, 2001. Upper row displays the oxygen ENA images in the 96-180 keV range, second row 27-39 keV hydrogen, and third row 60-119 keV hydrogen. All ENA images were obtained with a 4-minute integration. Dipole field lines of L-shells 4 and 8 are plotted at four local times for reference. IMAGE was in the northern hemisphere on the nightside for all images. The bottom row shows the auroral images simultaneously obtained by the Far Ultra Violet (FUV) Wide Imaging Camera (WIC) onboard IMAGE [*Mende et al.*, 2000]. The substorm onset was seen at 12:36 UT. Note that the high-altitude intensification in the oxygen image indicated by the red arrow. A slight increase is also visible on the high-altitude nightside in the hydrogen ENA images, but it is much more gradual.

**Figure 1.** Summary of the HENA observations starting at 12:30 UT on 28 October, 2001 for hydrogen and oxygen. Red arrows show oxygen injection, subsequent low-altitude ENA emissions, drift around and decay. Bottom row shows the FUV/WIC auroral images projected in magnetic coordinates.

At 12:47 UT, an increase in the oxygen intensity at high altitudes is seen together with strong emissions at low altitudes. We interpret this low-altitude enhancement as coming from the nearly-mirroring oxygen ions and the subsequent interaction with the upper atmosphere [*Roelof*, 1997]. High-altitude oxygen emissions have now spread to the duskside consistent with the direction of curvature-gradient drift. There is only a slight enhancement at low altitudes in the hydrogen images. Note also that the hydrogen enhancement for the 27-39 keV range appears in

the midnight-dawn sector, consistent with electric drifts in a skewed electric potential pattern as observed by *Brandt et al.* [2002] and successfully modeled by *Fok et al.* [2003] and *Ebihara and Fok* [2004].

At 13:00 UT, the high-altitude oxygen emissions have decreased and the low-altitude component of the oxygen emissions appears to have moved over to the dayside. Later at 13:10 UT, the oxygen emissions spread even further into the dayside. On the other hand, the hydrogen emissions display a continuous increase on the nightside with some increase around dusk during the substorm recovery, owing to the enhanced convection. This gradual increase in hydrogen cannot be attributed to the decreasing distance of the IMAGE satellite to the source region. The reason is that the pixel size is much smaller than the extent of the source region. Only when the source can be considered as a point source, then the intensity falls off as  $1/r^2$ . As the source extent grows the exponent in the denominator comes closer to zero. For these HENA images the ring current source is much large than the pixel size and therefore intensity does not vary with distance.

### 3. Simulations

#### 3.1. LFM Substorm During a IMF Southward Turning

The LFM model used in this study is described in detail in *Fedder et al.* [1995], *Mobarrry et al.* [1996] and *Slinker et al.* [1998]. The model solves the ideal MHD equations in a distorted spherical grid that extends 24 earth radii ( $R_E$ ) sunward of the Earth to 300  $R_E$  tailward and 90  $R_E$  in the Y and Z direction. The inner boundary is a sphere with a radius of 3.2  $R_E$  centered on the Earth. Field-aligned currents are mapped from this boundary to the ionosphere, where electric

potential is solved. The solution for the potential then provides an electric field that is mapped back to the inner boundary where it is used as a boundary condition for the MHD evolution.

In this study, the magnetosphere reconfiguration is driven by a southward turning of the interplanetary magnetic field (IMF), which is northward for an extended period of time. The IMF remains southward for 2 hours and then turns back to northward. Figure 2 shows the IMF history and snapshots of magnetic field lines projected into the SM X-Z plane. Solar wind velocity ( $V^{sw}$ ) and density ( $n^{sw}$ ) are kept constant during the simulation, with  $V_x^{sw} = -400 \text{ km}\cdot\text{s}^{-1}$ ,  $V_y^{sw} = V_z^{sw} = 0$ , and  $n^{sw} = 6.53 \text{ cm}^{-3}$ . The interplanetary magnetic field lines in Figure 2 are traced from the X-axis at every  $2 R_E$ . Geomagnetic field lines are traced from the model inner boundary on the noon-midnight meridian at every  $3^\circ$  starting from  $48^\circ$  latitude. As shown in Figure 2, the magnetosphere is closed after a long period of northward IMF ( $t_0$ ). Then the southward turning of IMF starts reconnection on the dayside and open up of field lines at high latitudes ( $t_1$ ). The magnetosphere gradually becomes longer and the plasma sheet is thinner ( $t_2$ ). Between  $t_2$  and  $t_3$ , reconnection has initiated in the magnetotail and an X-line is formed at about  $25 R_E$ . Since then dipolarization takes place, field lines are closing up and the newly formed closed flux tubes convect earthward ( $t_4$ ). The IMF then turns back to northward. The magnetosphere gradually returns to its initial state ( $t_5$ ).

**Figure 2.** Input IMF Bz as a function of time for the LFM model and snapshots of the MHD field lines projection on SM X-Z plane.

### 3.2. Solar Wind Inflow and Polar Wind, Auroral $O^+$ Outflow

We initiate protons and  $O^+$  from their representative source regions. The subsequent ion trajectories are calculated in the time-varying LFM fields using the test-particle code of *Delcourt*



*et al.* [1993; 1994]. As per *Moore et al.* [2005], solar wind protons are initiated over the YZ plane at  $X_{sm} = 15 R_E$ . The source flux is constant with time and is equal to  $n^{sw} \cdot V^{sw} = 2.6 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ . Ions are released randomly in the thermal energy range of 0–10 eV, pitch angle range of 0–180°, gyro-phase angle range of 0–360° in the  $E \times B$  frame from  $t = -6$  hours to the end of the LFM run ( $t = 3$  hours). Once the ions are initiated, they are picked up by the solar wind flow. We start at negative times such that ions have enough time to travel from the upstream region to the magnetosphere and well populate the magnetosphere at  $t = 0$ . The magnetosphere configuration at times less than zero is kept as that at  $t = 0$ . In total, 100 millions solar wind protons are released. Among them only a few percent enter into the magnetosphere. The rest of them just flow around the magnetosphere and are lost downstream.

For polar wind, protons are released on a sphere of  $4 R_E$  radii at magnetic latitudes above 55° with energy of 50–100 eV, all phase angles, pitch angle of 170°–180° in northern hemisphere and 0°–10° at south [*Moore et al.*, 2005]. Ions are initiated from –15 to 3 hours with a constant flux of  $7.1 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ . We have assumed polar wind escaping flux is relatively unaffected by auroral acceleration processes and geomagnetic activity [*Moore et al.*, 1999]. We start releasing polar wind protons (–15 hours) well before the start time of solar wind ions (–6 hours) because it takes longer time for low-energy polar wind ions to travel from the polar region to the magnetosphere. A total of 500,000 polar wind ions are released.

For the auroral wind, 2 million  $O^+$  are released from the topside ionosphere at 1000 km altitude from 60° to 90° latitude at both hemispheres from –15 to 3 hours. However, the  $O^+$  source flux  $F$ , thermal energy  $E_{th}$  and parallel energy  $E_{\parallel}$  are driven by the local MHD parameters as follow:

$$F [\text{cm}^{-2}\text{s}^{-1}] = 10^9 \left( 0.1 N_{\text{mag}} \right)^{2.2} + 1.1 \times 10^8 S_{\text{IK}}^{1.26} \quad (1)$$

$$E_{\text{th}} (\text{eV}) = 0.1 \text{ eV} + 1.6 S_{\text{IK}}^{1.26} \quad (2)$$

$$E_{\parallel} (\text{eV}) = E_{\text{th}} + e\Phi_{\parallel} \quad (3)$$

$$\begin{aligned} \text{where } \Phi_{\parallel} &= 1500 (J_{\parallel} - 0.33)^2 & \text{if } J_{\parallel} > 0.33 \mu\text{A}/\text{m}^2 \\ \Phi_{\parallel} &= 0 & \text{if } J_{\parallel} < 0.33 \mu\text{A}/\text{m}^2 \end{aligned}$$

$N_{\text{mag}}$  is the magnetospheric density in  $\text{cm}^{-3}$  at the LFM inner boundary at  $3.2 R_E$ .  $S_{\text{IK}}$  is the LFM ionospheric Joule heating in  $\text{mW}/\text{m}^2$  mapped to 1000 km altitude.  $\Phi_{\parallel}$  is the parallel potential drop, which is estimated as shown from the upward field aligned current at the ionosphere. All of the physical parameters used in Eq. (1) are derived from observations. The outflow description comes from *Strangeway et al.* [2005] and *Zheng et al.* [2005]. They found the two primary energy sources of ion outflow are soft electron precipitation and dissipation of downward Poynting flux. In Eq. (1) we use magnetospheric density and Joule heating as proxies for electron precipitation and Poynting flux, respectively. The temperature dependence on Poynting flux shown in Eq. (2) is given by *Strangeway* [private communication]. The parallel potential drops in Eq. (3) are based on the Knight-like relation given by *Lyons* [1981], based on the current systems from the global simulation.  $\text{O}^+$  are released at randomly selected phase angles. Pitch angles are determined from  $E_{\text{th}}$  and  $E_{\parallel}$ .

Figure 3 shows the MHD parameters and the corresponding auroral wind outflow parameters at 1000 km altitude at  $t = 0$  and 52 minutes ( $t_0$  and  $t_2$  in Figure 2). In the plots, Sun is up and magnetic latitudes of  $60^\circ$ ,  $70^\circ$  and  $80^\circ$  are depicted. The magnetospheric density is mapped along dipole field lines from the LFM inner boundary to 1000 km altitude, assuming constant density along field lines. As shown in Figure 3, at  $t_0$ , the magnetospheric particle and energy sources for  $\text{O}^+$  outflow are strongest on the dayside at high latitudes, where reconnection

takes place. As a result the strongest outflow flux and energy are also located on dayside high-latitude region. At  $t_2$  when the IMF has been southward for 52 minutes, strong outflow extends to lower latitudes and also to dawn and dusk local times. The highest  $O^+$  parallel energy is found in the noon-dusk sector, where the parallel potential drop (upward field aligned current) is the strongest.  $\Phi_{\parallel}$  is strongest on the dusk side because the sign of the vorticity in that boundary layer is preferentially such as to drive current upward from the ionosphere, yielding larger parallel potential drops needed to drive magnetospheric electrons into the ionosphere. However, these auroral features are indeed present in the evening as well as the dusk to afternoon hours, but are more transitory in association with the substorm. In fact, a clear westward traveling surge begins near midnight and moves toward the dusk region, producing a peak parallel potential drop of  $\sim 1$  kV at about 01:27 hrs into the simulation.

Figure 3. MHD conditions and auroral outflow parameters at 1000 km altitude at  $t = 0$  and 52 minutes.

The global  $O^+$  fluence that our model yields for this simulation run ranges from  $2 \times 10^{25}$  to  $8 \times 10^{26}$  ion/s. The range given by *Yau et al.* [1988] in their Figure 4., from their statistical study for Dst between zero and 60 nT (the range matching our simulation results) and for F10.7 in the high range from 100-150, is  $3 \times 10^{25}$  to  $2 \times 10^{26}$  ion/s. Our simulation is for a single discrete substorm, so it is expected that our short-lived peak flux would exceed their statistical average somewhat. Our Polar Wind  $H^+$  fluence ( $1 \times 10^{26}$  ion/s) is in close agreement with the total  $H^+$  fluence given by *Yau et al.* [1988] in the above cited figure.

### 3.3. Calculation of Density and Pressure in the Magnetosphere

Similar to the approach in *Moore et al.* [2005], the entire simulation domain (  $X = -70$  to  $15 R_E$ ,  $Y = -30$  to  $30 R_E$ ,  $Z = -30$  to  $30 R_E$ ) is divided into volume elements of  $1 R_E^3$ . In this dynamic case, we also divided the time in intervals of  $\Delta t$ . The density in volume bin  $j$  at time  $t$  contributed by particle  $i$ , which passes through bin  $j$  between  $(t - 0.5 \Delta t)$  and  $(t + 0.5 \Delta t)$ , is given by:

$$n_{ij}(t) = F_i(t_i) |\cos \alpha_i(t_i)| dA \frac{T_{ij}}{V_j} ; \quad dA = \frac{A}{N_{\Delta t}} \quad (4)$$

where  $F_i$  is the ion source flux, which is a function of  $t_i$ , the time particle  $i$  is launched,  $\alpha_i$  is the initial pitch angle,  $dA$  is the area of the source surface allocated to each particle, that is the total source surface area,  $A$ , divided by number of particles launched in  $\Delta t$  ( $N_{\Delta t}$ ),  $T_{ij}$  is residence time of particle  $i$  in bin  $j$ , and  $V_j$  is the volume of bin  $j$ , that is  $1 R_E^3$  in our case. Note that  $F_i$  and  $\alpha_i$  in the auroral wind case depend on the time of ejection,  $t_i$  (Figure 3).

The density in bin  $j$  at time  $t$  is just the summation of all particles that pass through bin  $j$  between  $(t - 0.5 \Delta t)$  and  $(t + 0.5 \Delta t)$ :

$$n_j(t) = \sum_i n_{ij}(t) \quad (5)$$

Once densities are calculated, the total (dynamic plus kinetic) pressure at bin  $j$  is given by:

$$P_j(t) = \sum_i P_{ij}(t) = \frac{2}{3} \sum_i n_{ij}(t) E_{ij}(t) \quad (6)$$

where  $E_{ij}$  is the average energy of particle  $i$  in bin  $j$ .

### 3.4. The Comprehensive Ring Current Model

As described above, the ion density and pressure in the magnetosphere are established by tracking particle energies along their trajectories. However, the LFM model generally underestimates the electric field in the inner magnetosphere. This is a common problem of ideal MHD models. As a result, the test-particle calculation will underestimate the ion penetration into the ring current region and the ion fluxes there. To resolve this problem, we use the simulated ion density and mean energy at the inner plasma sheet as boundary conditions to a kinetic ring current model to calculate the ion distribution in the inner magnetosphere. The ring current model we employed is the Comprehensive Ring Current Model (CRCM) described in *Fok et al.* [2001]. The CRCM calculates the ring current ion fluxes and ionospheric potentials in a self-consistent manner. The two main equations solved by the CRCM are:

$$\frac{\partial f_s}{\partial t} + \langle \dot{\lambda}_i \rangle \frac{\partial f_s}{\partial \lambda_i} + \langle \dot{\phi}_i \rangle \frac{\partial f_s}{\partial \phi_i} = -v \sigma_{sH} \langle n_H \rangle f_s - \left( \frac{f_s}{0.5 \tau_b} \right)_{\text{loss cone}} \quad (7)$$

$$\nabla \cdot (-\vec{\Sigma} \nabla \Phi) = J_{\parallel} \sin I \quad (8)$$

where  $f_s$  is distribution of ring current species  $s$ .  $\lambda_i$  and  $\phi_i$  are the magnetic latitude and local time at the ionosphere, respectively.  $f_s$  is a function of  $\lambda_i$ ,  $\phi_i$ , first and second adiabatic invariants, and is assumed to be constant along a field line. Equatorial fluxes can be obtained by mapping  $f_s$  along field lines from the ionospheric grid to the equator.  $\langle \dot{\lambda}_i \rangle$  and  $\langle \dot{\phi}_i \rangle$  are the bounce-average velocities of species  $s$  on the ionospheric grid.  $\sigma_{sH}$  is charge exchange cross sections for the ring current species  $s$  with neutral H.  $\langle n_H \rangle$  is the bounce-averaged neutral density of H.  $\tau_b$  is bounce period.  $\vec{\Sigma}$  is a tensor representing ionospheric Hall and Pedersen conductance.  $\Phi$  and  $J_{\parallel}$  are the ionospheric potential and field aligned current.  $I$  is the magnetic dip angle. Eq. (7) represents a drift-loss model of the ring current species  $s$  with the consideration of charge exchange and loss-

cone losses. The ionospheric field aligned current in Eq. (8) is calculated from the non-zero divergence of the perpendicular current contributed by all the ring current species. In this study, both ring current  $H^+$  (originated from solar wind and polar wind) and  $O^+$  (originating from auroral wind) are considered in the calculation of  $J_{\parallel}$  in Eq. (8). This method produces improved simulation of the convection electric field and ring current strength in the inner magnetosphere, as described below.

## 4. Simulation Results

### 4.1. Pressure Enhancement in the Plasma Sheet

We calculate the proton and  $O^+$  pressure in the entire simulation domain during the event as described in Section 3.3. Figure 4 shows the proton (solar wind plus polar wind) pressure on X-Z and X-Y planes at 60 and 80 minutes after the IMF southward turning. In both cases, the lobes are occupied by polar wind plasma while the plasma sheet is a mixture of polar and solar particles. At 60 minutes (left panels) when substorm onset has just commenced, thin plasma sheet was developed. As dipolarization continues, twenty minutes later (right panels), the lobes are well filled with polar wind ions. At the same time, a plasmoid is formed and is streaming tailward. At this time, a pressure peak is found at  $\sim 10 R_E$  in the dusk-midnight sector. These are protons being energized and drift earthward from the plasma sheet during substorm expansion.

Figure 4.  $H^+$  pressure on X-Z and X-Y planes at 60 minutes (left panels) and 80 minutes (right panels).

Figure 5 shows the simulated  $O^+$  pressure at the same times as shown in Figure 4. At 60 minutes (left panels) at the substorm onset, high  $O^+$  pressure is observed in the near-earth lobe

and plasma sheet regions. The blob seen on the equatorial plane on the dawn side at  $\sim 30 R_E$  is the high pressure from the tailward streaming  $O^+$  away from the newly formed reconnection X line. Twenty minutes later (right panels), the high-pressure region extended to low latitudes and to the duskside plasmas sheet. The high pressure on the duskside of the plasma sheet for  $x < -20 R_E$  is coming from strong outflow parallel energy in the ionospheric source region during the growth phase (bottom-right panel, Figure 3). A strong pressure peak is seen at the equatorial plane at  $\sim 2100$  MLT at  $12 R_E$ . These are particles flowing earthward from the reconnection region or particles energized locally by dipolarization. Both the proton and  $O^+$  peaks are located in the dusk-midnight sector. However, the  $O^+$  enhancement is stronger and extends to broader region.

Figure 5.  $O^+$  pressure on X-Z and X-Y planes at 60 minutes (left panels) and 80 minutes (right panels).

In order to understand why the  $O^+$  pressure increases significantly during substorm dipolarization, we examine individual  $O^+$  trajectories and their energy changes during the event. Figure 6 plots the trajectory of an auroral  $O^+$ , which passes through the pressure peak at 80 minutes as shown in Figure 5. Particle trajectory is projected on the X-Z and X-Y plane and the trace is painted by the instantaneous ion energy. The lower 4 panels of Figure 6 plot the temporal variation of ion total energy, parallel energy, perpendicular energy and magnetic moment, which is normalized by the initial value. This oxygen ion is released at  $\sim$  zero hour. The initial energy is 18 eV. The ion travels along the field line until it is picked up by the strong convection during southward IMF. It then convects anti-sunward to the plasma sheet. By the time ( $\sim 80$  minutes) the ion comes close to the plasma sheet, substorm onset has been triggered. Fast MHD earthward

flow during substorm expansion pushes field lines and the ion inward and simultaneously energizes it sharply to almost 2 orders of magnitude increase in energy. This fast MHD flow is equivalent to the strong inductive electric field in electromagnetic theory during magnetic reconfiguration. Both the  $O^+$  parallel and perpendicular energy grow sharply at this time. The magnetic moment also increases in a similar way, indicating the energization process is highly non-adiabatic. It is evident that the gyroperiod of the heavy ion is comparable with the time scale of the field variation so that the adiabaticity of magnetic moment is violated. We do not show in Figure 6 the variation of the second adiabatic invariant because it is difficult to compute. In fact, the violation of the second invariant occurs before the first invariant does owing to the longer time scale associated with bounce motion than gyration. The large increase in parallel energy as shown in Figure 6 implies serious violation of the second invariant. When the ion encounters the high-B region, because of the large energy acquired, it starts gradient-curvature drift to the dusk sector.

Figure 6.  $O^+$  trajectory projected on X-Z and X-Y planes. The lower two panels are ion energy and normalized magnetic moment during the time of flight.

#### 4.2. Flux Enhancements in the Ring Current Region

The pressure enhancements seen in the near-Earth plasma sheet after substorm onset (Figures 5 and 6) in theory should propagate inward to the ring current region. However, as mentioned above, the convection electric field in the inner magnetosphere predicted by the LFM model is weaker than it should be. Therefore, using the test-particle-MHD approach could not reproduce flux enhancement in the ring current often seen during storms and substorms. To resolve this problem, we calculate the ion distributions in the inner magnetosphere ( $R_o < 8 R_E$ )



using the CRCM. The potential drop across the CRCM poleward boundary at  $68.4^\circ$  latitude in the ionosphere is taken from the LFM output (Figure 7). The test-particle-LFM results (density and mean energy) are used to specify the CRCM boundary condition at the equator at  $8 R_E$ . Eq. (7) is then solved with the magnetic field specified by the LFM model and electric field (potential) calculated from Eq. (8). Figure 8 shows the CRCM boundary condition ( $H^+$ ,  $O^+$  density and mean energy) at the equator at  $8 R_E$  at the time of 64 minutes, that are calculated using the approach described in Section 3.3. The distribution at the boundary is assumed to be a bi-Maxwellian ( $T_{\parallel} \neq T_{\perp}$ ). It can be seen in Figure 8 that at this time during the substorm expansion,  $H^+$  (mixture of polar and solar wind particles) at  $8 R_E$  is denser but colder than  $O^+$ . Moreover, the  $H^+$  temperatures are pretty isotropic but noticeable anisotropy in  $O^+$  temperatures is seen, especially in the dusk-midnight sector. The  $O^+$  parallel energy is higher than the perpendicular energy, indicating that  $O^+$  energization is preferential in the parallel direction in that region. Field-aligned distribution has been observed at the geosynchronous orbit [Mauk and McIlwain, 1975] and is reproduced by test-particle simulations of Delcourt [2002] and Mauk [1986]. The strong acceleration in the field-aligned direction is associated with the violation of the second adiabatic invariant [Mauk, 1986]. For a given energy, the bounce period of  $O^+$  is longer than that of  $H^+$  so that in some cases, the second adiabatic invariant of  $O^+$  is not conserved while it is conserved for  $H^+$ .

Figure 7. Potential drop in kV across the CRCM poleward at the ionosphere.

Figure 8. CRCM boundary densities and mean energies of  $H^+$  (upper panels) and  $O^+$  (lower panels) at  $8 R_E$  equatorial distance at time = 64 minutes, calculated from the test-particle-LFM

models.

We run the CRCM throughout the event with magnetic field updated every 5 minutes and boundary flux at  $8 R_E$  updated every 4 minutes. The initial distributions of  $H^+$  and  $O^+$  are taken from the quiet time distribution measured by the Active Magnetospheric Particle Tracer Explorers (AMPTE) / Charge Composition Explorer (CCE) spacecraft [Sheldon and Hamilton, 1993]. Figure 9 plots the temporal variations of  $H^+$  and  $O^+$  total energies inside  $8 R_E$ . At the beginning during quiet time,  $H^+$  energy content is much higher than  $O^+$ . This is consistent with observations that  $H^+$  is the dominant species at quiet times [Young *et al.*, 1982; Hamilton *et al.*, 1998]. In the first hour before the onset, both energies are fairly constant with time. A slightly decrease in  $H^+$  energy is seen in this hour. This decrease in particle energy (or flux) is known as flux dropout during substorm growth phase [Baker and McPherron, 1990; Sauvaud *et al.*, 1996]. The  $O^+$  energy does not show such dropout due to the strong outflow during the growth phase. After the substorm onset at  $\sim 60$  minutes, both  $H^+$  and  $O^+$  total energies increase. However, the  $O^+$  energy increases much faster than that of  $H^+$ . At  $\sim 100$  minutes, the  $O^+$  energy exceeds that of the  $H^+$  and is kept rising even after the northward turning of the IMF at 120 minutes. The faster energy increase of  $O^+$  than  $H^+$  comes from the fact that there are higher  $O^+$  particle and energy influxes at the CRCM model boundary. All ions are continually accelerated in the ring current region by the convection. However, the ratio of energy gain  $\Delta E_{O^+} / \Delta E_{H^+}$  in the ring current is predominantly determined by the boundary distributions, which are controlled by energization processes in the plasma sheet. The total energy of  $H^+$  and  $O^+$  in the ring current region ( $r < 8 R_E$ ) at 160 minutes are  $1.9 \times 10^{31}$  keV, which would produce a surface magnetic depression of 75 nT [Dessler and Parker, 1959; Sckopke, 1966].

Figure 9.  $H^+$  (dashed line) and  $O^+$  (solid line) total energies inside  $8 R_E$  during the substorm event.

As shown in Section 2, IMAGE/HENA observes quick rise and decay of oxygen ENA during substorms. Our simulations also show large increase in  $O^+$  flux in response to substorm expansion. It is interesting to see whether our simulation reproduces the observed oxygen ENA signatures during a substorm. Figure 10 (upper panels) show the HENA 50-180 keV O images at three times during the substorm on 28 October 2001, the same substorm we discussed in Section 2. Figure 10a is the image taken at early substorm expansion, 9b late expansion and 9c in the recovery phase. The bottom panels of Figure 10 are the CRCM simulated equatorial  $O^+$  flux also at the beginning, at the peak of substorm injection, and during the recovery. The corresponding O ENA emissions are depicted in the middle panels. Arrows are placed in the top and middle panels of Figure 10 to highlight the similarities between observations and simulations. At the early expansion phase (left panels, Figure 10), the simulated injection boundary (the earthward edge of the injected plasma cloud) is located at  $\sim 5 R_E$ . At this time both the HENA data and simulated ENA image show soft enhancements at high altitudes (arrows). The ENA emissions near the Earth are produced from ions with mirror points at low altitudes. Note that the ion pitch-angle distribution is field aligned and neutral hydrogen density increases with decreasing altitude. The combined effects yield a stronger emission at low altitudes. As the event continues (middle panels, Figure 10), the simulated injection boundary moves inward to the  $\sim 3 R_E$ . Both simulated and observed ENA images show strong fluxes at low altitudes. Again these strong emissions are coming from charge exchange loss of field aligned ions. In addition to the strong emission near the Earth, there is a local maximum at high altitudes in the dusk-midnight sector.

The emissions here are from ions that are mirroring near the equator. This second ENA peak is more obvious in the simulated image than in the observed one. During the recovery of the substorm (right panels, Figure 10), the convection strength subsides. The injected oxygen ions drift westward to the dayside. As a consequence, strong ENA emissions are found on the dayside in both the simulation and HENA data.

Figure 10. Bottom panels: simulated equatorial  $O^+$  fluxes. Middle panels: simulated  $O$  ENA emissions. Top panels: HENA 50–180 keV  $O$  images at three times during a substorm on 28 October 2001.

Although our LFM-Delcourt-CRCM simulation reproduces qualitatively the observed oxygen ENA features during a substorm, there are quantitative differences between the model and data. For this particular substorm the 28 October 2001, it takes 21 minutes (upper panels, Figure 10) from the initiation of ENA enhancement to its maximum and 35 minutes from peak emission to substantial decay. The time scales in the simulation are longer (44 and 52 minutes). The discrepancy in timing may come from the fact that the LFM substorm presented here is not as strong as the one on 28 October 2001. The southward IMF in the LFM simulation is only 5 nT. With a more negative IMF  $B_z$ , the transition between different phases of the substorm would be faster. Strong southward IMF would also produce strong convection that pushes ions deeper inward and shortens the decay lifetimes. Another noticeable difference between the HENA and the simulated  $O$  fluxes is that HENA images exhibit spatially smoother emissions than the simulation. However one should keep in mind the angular-scattering problem in the HENA oxygen data (see Section 2) when comparing simulated oxygen ENA fluxes with HENA images.

The two-band structure in oxygen ENA emission predicted by the CRCM (middle panel, Figure 10) may be blurred out in the HENA data due to scattering at the instrument front foil.

## 5. Discussion

It is well known that the  $O^+/H^+$  ratio increases during magnetic storms and substorms [Young *et al.*, 1982; Hamilton *et al.*, 1998; Roeder *et al.*, 1995; Daglis 1997; Mitchell *et al.*, 2003; Nose *et al.*, 2005]. The simulations presented in this paper provide quantitative assessment on storm and substorm processes that are accountable for the increase of the  $O^+/H^+$  ratio. During storm times when convection are strong, magnetospheric energy dissipated into the ionosphere in the forms of enhanced particle precipitation, Joule heating and parallel potential drop. All these processes stimulate the up flowing of ionospheric  $O^+$  (Figure 3). Magnetospheric energy input to the ionosphere also rises during substorms and causes the increase of  $O^+$  outflow. However, there is a time lag (tens of minutes) between enhanced ionospheric outflow and resulting enhanced pressure in the magnetosphere. In addition to enhanced  $O^+$  outflow, the inductive electric field associated with substorm magnetic reconfiguration in the magnetotail energizes the pre-existed  $O^+$  in a highly non-adiabatic manner. This substorm associated energization produces rapid intensification of heavy ions without noticeable time lag. On the other hand,  $H^+$  is found to be less susceptible to storm and substorm activity [Kistler *et al.*, 2005]. As a result,  $O^+/H^+$  ratio increases with increasing geomagnetic activity.

IMAGE/HENA observed instant response of oxygen ENA to substorm expansion [Mitchell *et al.*, 2003]. A burst of oxygen ENA is seen at the time of auroral brightening (Figure 1). The source of this  $O^+$  enhancement is not fully determined yet. Two potential candidates are: direct injection of  $O^+$  from the ionosphere [Sheldon *et al.*, 1998] and energization of the pre-

existing  $O^+$  [Delcourt 2002]. *Sheldon et al.* [1998] observed a  $O^+$  enriched field aligned beam at  $\sim 40$  keV from particle detector on the POLAR satellite. This population existed from  $L = 3-7$  for a duration of longer than 2 hours. Thus this long-lived field-aligned signature is not the same bursty feature seen by IMAGE/HENA during substorms. Upgoing oxygen ions are also seen routinely from FAST [Kozyra, private communication], CRRES [Rubin *et al.*, 1995] satellites. However, the energies of the upflowing ions are below one keV. For direct-injection mechanism, the energy of the outflow ions must be high enough ( $> \text{few keV's}$ ) such that the bounce time is comparable with substorm expansion time scale of minutes. Our simulation results support the mechanism of energization of pre-existing ions in the magnetosphere. As shown in Figure 6, it takes more than an hour for the oxygen ion (initial energy = 62 eV) to convect from the dayside to the nightside. However, the ion arrives at the plasma sheet when dipolarization is taking place. The energy of the ion then sharply increases in two orders of magnitude to  $\sim 100$  keV in just a minute. After reaching high energy, the ion drifts westward to the dusk sector, where  $O^+$  pressure peak is established (lower right panel, Figure 5). In summary, direct injection of energetic  $O^+$  is seldom observed. Our simulations show energization of pre-existing  $O^+$  alone could produce the observed substorm  $O^+$  bursts.

We have shown in Figure 8 that  $O^+$  ions tend to have field aligned distribution in the plasma sheet during dipolarization. This field aligned feature during substorms is consistent with the simulation results of *Mauk* [1986] and ion measurements at the geosynchronous orbit presented by *Mauk and McIlwain* [1975]. However, some other observational and test-particle simulation studies found perpendicular pitch angle distribution of  $O^+$  ions after substorm onset [Lui 1996; Nose *et al.*, 2000; Sanchez *et al.*, 1993]. The discrepancy between these two findings may come from the time scale of the substorm reconfiguration. If at the point where

dipolarization is fast and both the first and second adiabatic invariants are violated, ions at that location are accelerated preferentially in the perpendicular direction. At the locations where dipolarization is relatively slow such that the first invariant is conserved but the second invariant is not, ions are primarily energized in the parallel direction. The LFM substorm we present here is a comparatively weak and slow substorm. The majority of the  $O^+$  ions experience less violation of the magnetic moment than the violation of the second invariant. As a result, field aligned distribution is found in the dipolarization region.

Energization of pre-existing ion mechanism can also explain the short-lived nature of the substorm  $O^+$  bursts. We have shown the field-aligned characteristics of substorm  $O^+$  (Figure 8) owing to the violation of the second adiabatic invariant during the acceleration process. Field-aligned ions with mirror points at low altitudes will encounter the dense neutral atmosphere and experience stronger collisional losses. The anisotropic ion distribution also stimulates wave growth that diffuses ions into the loss cone. If wave loss is included in our calculation, the decay time will be further shortened and has better agreement with the HENA data.

## 6. Summary

IMAGE/HENA observes rapid rise of high-energy (50–180 keV) oxygen ENA during substorm expansions and fast decay in the recovery phases. On the other hand, the hydrogen ENA emissions are relatively stable during substorms. We have performed a series of simulation to understand the physics controlling the growth and decay of  $O^+$  and  $H^+$  during a substorm. The LFM model is used to model a substorm that is triggered by a constant southward IMF of 5 nT. Using a test-particle code we launch millions of ions in the LFM fields from the solar wind, polar wind and auroral wind source regions hours before and throughout the event. Ion density,

parallel and perpendicular temperatures are calculated at the equator at  $8 R_E$ . These ion distributions are used as boundary conditions for the CRCM to calculate the detailed energy spectra of ring current  $H^+$  and  $O^+$ . The corresponding ENA fluxes are computed and compared with the HENA substorm data on 28 October 2001. We found

- (1) The simulation shows a rapid increase in  $O^+$  pressure in the plasma sheet during the substorm expansion. The changes in  $H^+$  pressure are relatively weak.
- (2) The calculated  $O^+/H^+$  energy ratio in the ring current region increases with increasing geomagnetic activity, consistent with observations.
- (3) The simulated O ENA emissions reproduce some observable substorm signatures from IMAGE/HENA but the calculated ENA growth and decay time scales are longer than observations.
- (4) From our simulations and HENA observations, it appears that  $O^+$  bursts seen during substorms can be explained by non-adiabatic energization of pre-existing  $O^+$ , without the contribution from direct injection of ionospheric ions.
- (5) The calculated  $O^+$  enhancements are found to have pitch angles favoring the field-aligned direction. This pitch-angle distribution partly explains the rapid decay of the observed substorm  $O^+$  bursts.

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